

FINAL REPORT

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GRANT TITLE: Physiology of freely diving white whales,  
*Delphinapterus leucas*

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OBJECTIVE: To assess the aerobic diving capability of white whales by examining dive behavior, respiratory rate, and the onset of lactic acid accumulation in the blood of whales performing voluntary dives.

APPROACH: The performance of trained white whales was assessed during swimming and diving trials. During diving sessions, the whales made repetitive dives to a test platform that was suspended from a boat to depths up to 300 meters. Experimental sessions consisted of 2-6 repetitive dives of varying duration but constant depth followed by blood sampling. In addition, the whales' non-exercise breath hold capability were determined by collection of serial blood samples while animals voluntarily held their breath. In all studies blood samples were measured for changes in  $P_{O_2}$ ,  $P_{CO_2}$ , pH, hematocrit (Hct), and plasma lactate and glucose concentrations.

ACCOMPLISHMENTS: A total of 457 dives were recorded during this study with the deepest to 300 m and longest 13.3 minutes. Respiratory frequency increased with increasing dive time. The maximum post dive respiratory rate was as high as 9.6 breaths per minute (bpm) which was 6 times the normal resting rate of 1.6 bpm. Associated with the increase in respiratory rate were changes in plasma lactate and glucose concentrations. These changes were affected by 1) total dive time and 2) duration of the post dive surface interval in relation to dive time within a bout of serial diving. Plasma lactate increased 2-2.4 times resting concentration ( $0.7 \pm 0.2 \text{ mmol} \cdot \text{l}^{-1}$ ) following single dives with durations greater than 9 min ( $P < 0.05$ ,  $t = -3.63$ ,  $n = 11$ ). The range of post dive glucose concentrations for both

animals was  $5.4-8.0 \text{ mmol}\cdot\text{l}^{-1}$  compared to baseline concentrations of  $6.1-6.5 \text{ mmol}\cdot\text{l}^{-1}$ .

Each whale made three sedentary breath-hold dives with mean durations of  $16.1 \pm 0.4 \text{ min}$  (maximum 17.0 min) and  $14.8 \pm 1.5 \text{ min}$  (maximum 16.5 min). The  $P_{O_2}$  of the blood measured in the first minute of the breath-hold averaged 63.5 mm Hg (maximum 79 mm Hg), which decreased in the first 8 min to approximately 28 mm Hg, after 10 min,  $P_{O_2}$  remained fairly constant at 20-23 mm Hg. Conversely,  $P_{CO_2}$  increased linearly from 61 to 83 mm Hg ( $P < 0.05$ ,  $n = 34$ ,  $r^2 = 0.501$ ). The pH declined from 7.26 to 7.17 ( $P < 0.05$ ,  $n = 34$ ,  $r^2 = 0.293$ ). Hct did not vary significantly with the duration of breath-hold.

Together, the whales completed 207 boat follows trips during the study period. Speeds faster than  $3.1 \text{ m}\cdot\text{s}^{-1}$  resulted in a noticeable decrease in swimming effort of the female whale because a sizable stern wake was created which enabled the whale to 'surf' behind the boat. The male whale refused to boat follow at speeds greater than  $3.1 \text{ m}\cdot\text{s}^{-1}$ .

Both respiratory rate and blood chemistry changed in relation to swimming speed at the water surface. Breathing rate increased to a maximum of 5.5 bpm when swimming speed reached  $1.7-1.9 \text{ m}\cdot\text{s}^{-1}$ . For trials conducted at swimming speeds greater than  $1.9 \text{ m}\cdot\text{s}^{-1}$ , mean respiratory rate decreased with subsequent increases in swimming speed. Surprisingly, the lowest exercising respiratory rate (2.1 bpm) was observed during the fastest swimming trial ( $4.2 \text{ m}\cdot\text{s}^{-1}$ ). This low respiratory rate was likely due to a reduction in effort as a result of wake riding.

Mean plasma lactate concentration for both whales increased from  $0.7 \pm 0.2$  to  $1.8 \pm 0.6 \text{ mmol}\cdot\text{l}^{-1}$  ( $P < 0.05$ ,  $n = 14$ ) after swimming at  $2.5-2.8 \text{ m}\cdot\text{s}^{-1}$  for 10 min. Glucose decreased slightly in both whales but this decrease was only significant for the male. The post exercise glucose concentration decreased by 5-15 % of resting concentration ( $6.1-6.5 \text{ mmol}\cdot\text{l}^{-1}$ ).

SIGNIFICANCE: Aerobic dives are constrained by the total oxygen stored in the muscle, blood, and lung and the rate it is utilized. It is defined as the diving duration beyond which blood lactate levels increase above resting levels. ADLs have only been experimentally determined in two species of pinnipeds and the bottlenose dolphin. The ADL of Weddell seal's, *Leptonychotes weddelli*, was measured to be 18-20 min, 2.3 min in the California sea lion, *Zalophus californianus*, and 4.5 min in the bottlenose dolphin. In this study, we determined an ADL of 9-10 min for white whales. These are the first empirically determined

measurements of ADL for a cetacean other than the bottlenose dolphin.

PUBLICATIONS AND ABSTRACTS:

- Shaffer, S.A. Assessment of Physiological and Behavioral Adjustments in Diving and Exercise of Two Cetaceans Species, *Delphinapteras leucas* and *Tursiops gilli*. MSc Thesis, Marine Sciences Department, University of California at Santa Cruz CA. 92 pages, June 1996.
- Shaffer, S. A., D. P. Costa, T. M. Williams, and S. H. Ridgway 1997. Diving and Swimming Performance of White Whales, *Delphinapterus leucas*: An Assessment of Plasma Lactate, Blood Gas Levels, and Respiratory Rates. *Journal Experimental Biology*:200:3091-3099.
- Costa, D.P. and T E. Williams. In press. Marine Mammal Energetics. In *The Biology of Marine Mammals* ed John Reynolds and J. Twiss. Smithsonian Institution Press.
- Costa, D.P., N.J. Gales, and D.E. Crocker 1988. Blood Volume and Diving Ability of the New Zealand Sea Lion, *Phocarctos hookeri*. *Physiological Zoology* 71(2):208-213.
- Costa, D.P., D.E. Crocker, B.J. LeBoeuf and P. Webb. 1996. Foraging behavior of northern elephant seals using time depth recorders coupled with ARGOS satellite locations. Fifth European Conference on Wildlife Telemetry Strasbourg France August 1996
- Costa, D.P. Crocker, D.E. and M.E Goebel. The effect of foraging behavior on foraging energetics and maternal investment in northern elephant seals and fur seals. At "Energetics of reproduction in birds, mammals and reptiles: exploring new technologies an International Colloquium at Chize, France, October 1996.
- Costa, D.P. 1996. A Bioenergetic Model of the Evolution of the Pinnipedia. Secondary Adaptation to the Marine Environment Multidisciplinary International Congress at Poitiers France. September 1996
- Shaffer S. 1997. Dive duration and body mass: Is there a relationship? Physiological Ecology Meeting: JUNE 6-7 Owens Valley Laboratory, Bishop, CA

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